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Department of Geodetic Science and Surveying

BASIC RESEARCH FOR THE GEODYNAMICS PROGRAM

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The Ohio State University  
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Columbus, Ohio 43212

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## PREFACE

This project is under the supervision of Professor Ivan I. Mueller, Department of Geodetic Science and Surveying, The Ohio State University. The Science Advisor is Dr. David E. Smith, Code 921, Geodynamics Branch, and the Technical Officer is Mr. Jean Welker, Code 903, Technology Applications Center, both at Goddard Space Flight Center, Greenbelt, Maryland 20771.

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## **1. CURRENT TECHNICAL OBJECTIVES**

- 1. Optimal Utilization of Laser and VLBI Observations for Reference Frames for Geodynamics**
- 2. Utilization of Range Difference Observations in Geodynamics**
- 3. Estimation Techniques in Crustal Deformation Analysis**

## 2. ACTIVITIES

### 2.1 Earth Rotation Parameter Determination from Different Space Geodetic Systems

#### Introduction

Since the last report on this study, most of the work accomplished has centered on developing or obtaining adequate software to simulate and adjust VLBI (Very Long Baseline Interferometry) observations. Some work has also been done concurrently on making decisions regarding the overall study, such as on the handling of systematic effects and concerning possible station position choices. These decisions will be discussed first.

#### Decisions Regarding the Simulation and Adjustment of Data

Only a few further decisions regarding the simulation and adjustment of the LLR (Lunar Laser Ranging), SLR (Satellite Laser Ranging) and VLBI data have been made. Generally, the proposed procedures to be followed have changed little from that described in the last two reports on this study.

The simulation and adjustment of the SLR data will proceed as planned before, except that the oblateness of the earth (as represented by  $J_2$ ) will be properly taken into account. This will allow the regression of the nodes of the orbit of Lageos to be properly accounted for, thereby more realistically representing the true geometry of the situation.

For LLR, the situation remains unchanged. It has been confirmed with Dr. Peter Shelus of the University of Texas [personal communication, October, 1984] that ignoring the librations of the Moon should not be a problem if time spans under two weeks are being considered. The normal practice in LLR (for Earth orientation determinations) is to range to the single large Apollo 15 Hadley array, both to obtain stronger returns and to avoid libration effects involved in using multiple targets or targets away from the Moon's central meridian. For our purposes the geometry of this situation is fairly well represented by the assumption of a point mass Moon (over short periods).

Effectively no changes have been made in the proposed procedure for simulation and adjustment of the VLBI data.

The selection of the appropriate ground stations has been completed for the LLR and VLBI techniques. The LLR station list is limited by the only possible stations expected to be in operation in the next few years. These stations include: 1) the MLRS at McDonald Observatory, Texas, 2) Haleakala Observatory, Maui, Hawaii, 3) Ororua, Australia, 4) Grasse, France, and 5) Crimea Observatory, USSR.

The inclusion of the new USNO system at its current GSFC, Maryland, or its planned Richmond, Florida, location is also still a possibility. The station at Wettzell will not be considered due to the unlikelihood of it operating (in LLR mode) soon, the high latitude, and the poor weather at that site.

The VLBI station list will consist of the current four-station IRIS network, i.e., (1) Ft. Davis, Texas, (2) Richmond, Florida, (3) Westford, Massachusetts, and (4) Wettzell, West Germany. The station at Onsala, Sweden, will not be included since it will never be likely to observe more than once per month [W. Carter, personal communication, October, 1984], and because the geometry of its position is largely duplicated by the station at Wettzell.

A VLBI observing schedule for an "Atlantic Network" of Richmond, Westford, a station in France (which could be replaced by Wettzell), and the South African station has been prepared at NGS, since the South African station will likely be obtaining a MARK III system soon. A copy of this schedule will be sent here [W. Carter, personal communication, April 4, 1985], and may be used for later simulations which could be compared with the simulations using the IRIS network.

The addition of the long Europe-South Africa (north-south) baseline should greatly influence the sensitivity of the VLBI UT1 measurements. Although VLBI stations will also be operating soon for geodetic purposes in Shanghai, China, and in Kashima, Japan, they will not be considered in this study. This is basically because their (east-west) geometry would not add much to the current network, and partially because no schedules are available for observations from them. A north-south baseline from them to Australia might prove very useful, but no VLBI observatories dedicated to making observations for Earth orientation are currently planned there.

One question that has also been seriously considered concerning the simulation and adjustment of the data is how the many possible "systematic effects" should be considered (e.g., effects due to refraction, gravity field, tides, nutation, radiation pressure and atmospheric pressure on Lageos, etc.).

It would appear at first consideration that the addition of such effects to simulated data, and the removal of them by the same models in any adjustment would be pointless. However, in reality, the recovered effects may vary from the "true" simulated effects since (a) sampling errors may occur, and (b) many of these effects are not very separable (in the adjustment sense) from each other. To try to take this problem into account, the following procedure will probably be followed:

1. The complete set of simulations and adjustments will be done first without any such systematic effects considered.

2. An attempt to recover at least some of the effects (e.g., refraction?) from the simulated observations will be made. The recovery should be done for data with and without the same effect added, to see how recoverable such effects really are.

3. As time permits, further effects will be considered individually in a similar manner.

4. Eventually, important combinations or all possible such effects together may be looked at.

Certainly, further study will be made of this problem, which appears to be a common one whenever simulations are being done.

## Software

As already mentioned, most of the work done since the last report has centered on developing programs to simulate VLBI data ("SKEDVIP" and "VIP" described below) and obtaining a program which can adjust VLBI data (namely, a version of GEOLYN).

The program "SKEDVIP", which is used to read Mark III schedule files and output data for use by "VIP" has been completed and tested. The program reads files created by the Mark III "SKED" program in the format described in [Vandenburg and Schaffer, 1983]. The schedule files themselves have been obtained from NGS. The schedules are shifted in time by the program to fit any desired day and output in a format usable by the program "VIP".

Program "VIP", previously written by Yehuda Bock, then simulates the observations according to the given schedule and various other options specified (as described in [Bock, 1980]). However, several modifications have been made to this program, mostly to allow the simulated observations to be output for use by the program GEODYN. The many changes made include the following:

- \* Operation allowed now from batch or TSO.
- \* Program stored as routines in a load module library to allow for easier changing and so less disk space is used.
- \* Minor errors and printout problems have been eliminated.
- \* Schedule input is optionally accepted as provided by the "SKEDVIP" program.
- \* The correct source names and station numbers are properly kept track of throughout the program.
- \* Simulated data can be optionally output in GEODYN binary format.
- \* White noise can be optionally added to the simulated observations.
- \* Changes were made to allow all scheduled observations to be simulated even when station subnetting occurs (as is common in Mark III schedules).
- \* If desired, clock parameters may be eliminated from the solution (all clocks may be assumed perfect).
- \* Up to 60 earth orientation parameters are allowed in the batch version (e.g., up to 15 days of six-hour earth rotation and polar motion parameters).
- \* Sidereal time and conversion from mean to sidereal time are computed rigorously (using Newcomb's equation).
- \* Precession (Newcomb's) and Nutation (Woollard's) can optionally be added to the source positions when observations are simulated. (However, with this option in use, a solution in "VIP" is no longer done correctly.)



- \* Except when Precession and Nutation are applied to the source positions, "VIP" can still adjust the simulated data and provide a solution.
- \* Solutions using either delay or delay-rate data are possible, but solutions using both data types are no longer possible due to changes made by Bock (and storage space problems).

To actually process the simulated VLBI data, the effort to obtain a version of GEODYN capable of this was continued. Our last two reports described how the updates to GEODYN which would allow VLBI data to be processed had been accidentally left out of the 8210.1 production version, and our unsuccessful attempt in September, 1984, to obtain those updates. In October, it was decided at GSFC/NASA that the updates should be incorporated in GEODYN, so it was then necessary to wait for this new version (to be known as GEODYN 8210.7) to be prepared and tested. After several long delays, a tape containing (among other things) the 8210.7 source was received from Mr. N. Zelensky of EG&G on February 14, 1985.

However, since a load module of the program was not on the tape, and since we no longer had the required H-extended Fortran compiler, another tape was requested with the load module (and corrected versions of some of the other files). This was received on February 25, 1985, and by mid-March the 8210.7 version was working here. The VLBI Benchmark (test) run provided by Mr. Zelensky gave results here identical to his runs at EG&G.

It was also determined that although the program could be compiled successfully with the VS Fortran compiler (using the "LANGVL(66)" option), it could not be loaded as a program unless (a) the assembler subroutine "INCORE" was rewritten so as not to require the H-extended Fortran subroutine "IBCOM", or (b) a load module including the H-extended Fortran library subroutines could be linked against properly (which might be very complicated to do). Further work along these lines has been dropped, and will only be continued should it be necessary to actually change the program here.

The SOLVE program (version 8212.0), which allows combining the normal equations created by various GEODYN solutions has now also been fairly well tested. A test run using the normal equations ("E-Matrix") created by the VLBI Benchmark run was prepared and made at EG&G by Mr. Zelensky. This run was repeated here (both with a copy of Mr. Zelensky's E-matrix, and a new E-matrix output by the GEODYN 8210.7 program) and generally the same results were obtained.

Specifically, it appears that Mr. Zelensky is using a slightly later version of the SOLVE program than 8212.0 (even though we were informed in early 1984 by Ms. B. Putney of GSFC/NASA that 8212.0 was the latest version). Thus there are some minor differences in the program printouts, but fortunately they are negligible in the case of the parameter estimates or parameter variance-covariance matrices. A solution combining several sets of normal equations (several E-matrices) still needs to be done as a final test.

## Summary and Future Work

Except for some further test runs with GEODYN and SOLVE (for example, with simulated VLBI data, and with several sets of normal equations respectively) most of the major program development and acquisition seems to be complete. Work for the immediate future will include:

1. Making the above test runs.
2. Deciding on how to simulate the ERP (earth rotation parameter) data (and developing simple software to do so).
3. Making the final station choices for SLR and determining the observational accuracies to be used for all methods.
4. Developing software for ERP and station location plotting and comparison.
5. Possibly developing or obtaining software to combine (smooth) the ERP results from the individual systems for comparison.

As these items near completion, the complete simulation will be run for a short period (one day), and if successful, then run over the proposed one- to two-week length. Then examination of the results will follow, and with repetition of the simulation as necessary, to examine the various other problems mentioned in this and the previous two semiannual reports. Except for perhaps the final examination of the results all work should be finished by the time of the next report.

## References

- Bock, Yehuda (1980), "A VLBI Variance-Covariance Analysis Interactive Computer Program," Ohio State Univ. Dept. of Geodetic Science Rep. 298, Columbus.
- Vandenburg, N.R. and D.B. Schaffer (1983), "Standard Schedule File Format - Mark III Software Documentation," (GSFC/NASA).

## 2.2 Utilization of Range-Difference Observations in Geodynamics

### Introduction

As reported in the last semiannual status report, in order to investigate the effectiveness and the steady state response of the Simultaneous Range-Difference mode (SRD) method, the 7114-7115 baseline length for the period October-December, 1979, was estimated using real data. These baseline lengths were then compared with the corresponding ones as determined by the Range Dynamic mode (RD) through the GEODYN program at GSFC Geodynamics Branch. It was clear that both methods (i.e., SRD and RD) perform about the same with a bias of 17 cm (Thirteenth Semiannual Status Report, October, 1984).

At that point, therefore, no assessment could be made as to which baseline length is the correct one because both of the above methods are affected by model errors. Therefore, it was decided to first compute the baseline lengths through the Simultaneous Range Geometric mode (SRG). The reason for choosing the SRG method is that this method does not require any models of the orbit dynamics and of the reference frames.

Unfortunately, this SRG method being a strictly geometric method, it requires a strong geometry in order to produce meaningful baseline lengths. The only laser range data set that comprises this required geometry is the Main MERIT Campaign data set. Thus the only alternative is the computation of the baseline lengths among the stations which participated in the Main MERIT Campaign through the SRD, RD and SRG method provided that the geometry allows meaningful SRG solutions.

Based on these computations and taking into consideration that the baselines as estimated through the SRG method will constitute the standard of comparison, an inference can be made about which method (SRD--GEOSPP81 or RD--GEODYN) performs better. Even if this comparison would show that the normal data analysis through the RD method is perfect (modelwise), then the only advantage of the SRD method would be its economy in computer time and software package. Adding the possibility of model errors going into other satellites moving in lower altitude, then SRD has an additional advantage. On the other hand, if the baselines are statistically different, a residual analysis in the frequency domain (through time series analysis) will follow to identify sources producing these differences. These sources can be grouped into the following categories:

- \* Orbit Dynamics
- \* Reference Frames
- \* Tropospheric Refraction Models
- \* Near Critical Configuration Problems for the SRG method.

## Data Processing

The MERIT data set that is being analyzed in this investigation consists of about 30 tapes. Each tape contains approximately 250,000 observations distributed over 100 passes. These observations were collected by 58 stations that participated in the Main MERIT Campaign. Most of the MERIT data set has been available to us through the Crustal Dynamics Data Information System. This data set has been processed, and the starting epoch, ending epoch and the number of observations per station per pass for all the satellite passes observed by two or more stations have been obtained. Processing this data set we encounter many problems associated with the data format.

All these problems were resolved with the help of either Henry G. Linder (NASA/GSFC) or B.E. Shutz (Texas). The only unresolved problem was the one associated with the data recorded by station 7838 (Simosato, Japan), namely, some of these data records contain asterisks. Being afraid that there may have been something wrong with the functioning of this station, we decided not to use this station in the subsequent analysis, until we find out what this problem is.

Through the above process all the passes containing arcs simultaneously observed by four or more stations were identified and isolated. The nonsimultaneous laser range observations corresponding to these passes are utilized to generate the simultaneous ranges for the simultaneously observed arcs. The programs used to create the simultaneous observations for four or more stations have been completed and tested. These programs utilize the Chebychev interpolation method. The reasons for using this interpolation method were reported in the last semiannual status report. Also, in this interpolation process the "Data-Snooping" procedure developed by Baarda was incorporated to reject observations contaminated by blunders.

Processing the data through the SRG method, one may run into cases where ground stations and/or satellite targets have configurations for which a unique least squares adjustment in terms of coordinates may be impossible, even if the number of observations is sufficient and the coordinate system well defined. Such configurations, called critical, should be identified and rejected when the SRG method is performed. In order to become familiar with the nature of these problems and the ways to avoid them, the reports "Investigations of Critical Configurations for Fundamental Range Networks" by Georges Blaha and "Estimability and Simple Dynamical Analyses of Range, Range-Rate and Range-Difference Observations to Artificial Satellites" by B.H.W. van Gelder were studied.

Presently, the OSUGOP program is being worked on. This program was developed at The Ohio State University in 1972; OSUGOP is an acronym for The Ohio State University Geometric and Orbital Program. This program performs a least squares adjustment for station coordinates using optical or range observations in either geometric or dynamic mode (Reilly et al., 1972). This program will be used to process the data through the SRG method.

## Summary of Future Work

The next step will be to compute and apply to the observations the systematic corrections due to tidal motions of the observing stations and due

to troposphere.

The subsequent step will be to generate the Lageos initial state vector for the starting epoch of each pass, the short planetary ephemeris file for the time span of the observations, the coordinates of the pole and the variations in UT1 at the epochs of the observations.

Utilizing the information generated above, the baseline lengths will be estimated through the SRD (GEOSPP81), SRG (OSUGOP) and the RD (GEODYN) methods. The GEOSPP81 program should first be modified to be compatible with both the MERIT standards and the astronomical constants used to create the planetary ephemeris file.

After testing the estimated baselines statistically, an investigation will follow to analyze the effects of the systematic errors on the estimated baselines as propagated through these three methods (i.e., SRG, SRD, and RD). These effects depend on the relative orientation between the model hyperplanes (generated by the design matrices of these three methods) and the systematic error vector. Based on this and on statistical considerations, one may come up with systematic error sensitivity indicators that would give the percentage of the unknown systematic error propagated into the estimated baselines through the SRD and RD methods. This may be possible to achieve because the systematic error vector lies on a hyperplane perpendicular to the SRG model hyperplane.

Moreover, the estimated baselines will be analyzed on the basis of the compatibility numbers proposed by Schaffrin [private communication, 1985]. These numbers may explain the model and data compatibility as reflected into the estimated baselines.

In conclusion, this investigation, besides completing and testing the SRD method to be ready for use with real data, will also contribute to a better understanding of how one should expect the baselines to be contaminated by the systematic errors. This understanding is essential when plate tectonics are analyzed on the basis of baseline variations.

### References

- Blaha, G. (1971) "Investigations of Critical Configurations for Fundamental Range Networks," Ohio State Univ. Dept. of Geodetic Science Rep. 150, Columbus.
- Reilly, J.P., C.R. Schwarz and M.C. Whiting (1972), "The Ohio State University Geometric and Orbital (Adjustment) Program (OSUGOP) for Satellite Observations," Ohio State Univ. Dept. of Geodetic Science Rep. 190, Columbus.
- Van Gelder, Boudewijn H.W. (1978), "Estimability and Simple Dynamical Analyses of Range (Range-Rate and Range-Difference) Observations to Artificial Satellites," Ohio State Univ. Dept. of Geodetic Science Rep. 284, Columbus.

## 2.3 An Algorithm for Crustal Deformation Analysis

### Introduction

In recent years, the improvements in space measurement techniques made feasible the detection of crustal movements. Yet, an increasing number of observations and their accuracies are still not enough to reach reliable conclusions and operational models about the relevant deformation parameters over short time intervals.

In the meantime there exists the possibility of improving contemporaneous parameters of crustal deformations by embedding them in a more general data analysis algorithm in which a different nature of data, such as information provided by the long-term behavior of the crustal motions, can be combined with recent measurements.

From the sampling theoretical point of view, a possible estimation candidate that can be employed in such an analysis is the well-known mixed model estimation.

However, it is also likely that the prior information about the deformation parameters may not be compatible with the ones suggested by the current data simply because previous data may be representative only in the long-term average sense. But this condition by no means suggests that such information should be totally discarded from the analysis.

In the sequel, the conditions under which improvements can be obtained is examined even though the prior information is proven to be noncompatible within the scope of mixed model estimation technique.

### Linear Estimation in an Improved Gauss-Markov Model

Theorem: Let

$$y = Ax + u \quad (1)$$

be a linear model, where  $y$  is an  $n \times 1$  vector of observations,  $A$  is the  $n \times m$  mapping matrix of full rank,  $x$  is the  $m \times 1$  vector of unknown parameters with  $m < n$  and assumed to be deterministic in nature.  $u$  is the  $n \times 1$  vector of disturbances with the following assumed properties

$$\begin{aligned} u &\sim (0, \sigma^2 \Sigma_{uu}) \\ \Sigma_{uu} &> 0 \end{aligned} \quad (2)$$

If there exists an independent stochastic auxiliary information vector  $\bar{x}$  on  $x$  such that

$$\begin{aligned} \bar{x} &= x + e \\ e &\sim (0, \Sigma_{ee}) \\ \Sigma_{ee} &> 0 \end{aligned} \quad (3)$$

where  $e$  is the  $m \times 1$  vector of disturbances on  $x$ , then the "Best Linear Uniformly Unbiased Estimator" (BLUE)  $\hat{x}$  of  $x$  based on the resulting mixed

linear model

$$\begin{pmatrix} y \\ \bar{x} \end{pmatrix} = \begin{pmatrix} A \\ I \end{pmatrix} x + \begin{pmatrix} u \\ e \end{pmatrix} \quad (4)$$

is,

$$\hat{x} = (I + \sigma^{-2} \Sigma_{ee} N)^{-1} (\sigma^{-2} \Sigma_{ee} A' \Sigma_{uu}^{-1} y + \bar{x}) \quad (5)$$

whose dispersion matrix is given by

$$D(\hat{x}) = (\Sigma_{ee}^{-1} + \sigma^{-2} N)^{-1} \quad (6)$$

where

$$N \triangleq A' \Sigma_{uu}^{-1} A \quad ||$$

(For the proof of the theorem see [Theil and Goldberger 1961; Schaffrin 1983]).

Since one of the main effects of auxiliary information is to reduce the dispersion matrix of the estimates, the following corollary is of interest:

Corollary 1: The BLUE  $\hat{x}$  of  $x$  is a better estimate than the sample estimate  $\hat{x}_S$  of  $x$ , where

$$\begin{aligned} \hat{x}_S &= N^{-1} A' \Sigma_{uu}^{-1} y \\ D(\hat{x}_S) &= \sigma^2 N^{-1} \end{aligned} \quad (7)$$

in the sense of their corresponding dispersion matrices since

$$D(\hat{x}_S) - D(\hat{x}) = \sigma^2 N^{-1} - (\sigma^{-2} N + \Sigma_{ee}^{-1})^{-1} > 0 \quad || \quad (8)$$

However, the unbiasedness assumption, which plays a crucial role in deciding which estimator is best, can hardly be achieved in practice. Assume that the true but unknown form of the auxiliary information on the parameters is, in fact,

$$\bar{x} = x + s + e \quad (9)$$

where  $s \neq 0$  is an  $m \times 1$  vector of possible deviations. This in turn implies that  $E(\bar{x}) \neq x$ , then the estimate  $\hat{x}$  is no longer unbiased. It is easy to show that

$$E(\hat{x}) = x + (I + \sigma^{-2} \Sigma_{ee} N)^{-1} s \quad (10)$$

where the last term is the bias caused by the wrong prior information,

$$\text{bias} \triangleq Z = (I + \sigma^{-2} \Sigma_{ee} N)^{-1} s \quad || \quad (11)$$

Now, the next question is under what conditions can wrong prior information still be used to improve the estimates. Since the dispersion matrix of the estimated parameters is not affected by the possible form of prior information given in equation (9), the ordinal measure of betterness criterion used in corollary (1) cannot be used for comparison. Therefore another criterion is necessary.

Definition: Biased estimator  $\hat{x}$  dominates sample estimate  $\hat{x}_S$  iff

$$\text{MSE}(\hat{x}_g) - \text{MSE}(\hat{x}) > 0 \quad (12)$$

Clearly if (12) holds, then a cardinal measure of gain can be obtained by the trace of the same equation:

$$\text{tr}\{\text{MSE}(\hat{x}_g) - \text{MSE}(\hat{x})\} = \text{SMSE}(\hat{x}_g) - \text{SMSE}(\hat{x}) > 0 \quad (13)$$

Considering

$$\begin{aligned} \text{SMSE}(\hat{x}_g) &= \sigma^2 N^{-1} \\ \text{SMSE}(\hat{x}) &= \text{tr } D(\hat{x}) + \text{tr } sZZ^T s^T \\ \text{SMSE}(\hat{x}_g) - \text{SMSE}(\hat{x}) &= \text{tr}(D(\hat{x}_g) - D(\hat{x}) + sZZ^T s^T) > 0 \\ \text{tr}(D(\hat{x}_g) - D(\hat{x})) &> s^T Z^T Z s \quad || \end{aligned} \quad (14)$$

Thus the biased estimator  $\hat{x}$  is superior to the sample estimate according to the scalar mean square error (SMSE) cardinal measure of preference, which is equal to the trace of MSE, if its squared bias is less than the total decrease in variances of all  $m$  estimated  $x$  components. A necessary and sufficient condition for this to happen can be derived following the similar lines given in [Terasvirta 1980].

Corollary 2: A necessary and sufficient condition for the biased estimator  $\hat{x}$  to be superior to the sample estimate  $\hat{x}_g$  in the sense described in equation (13) is

$$\sigma^{-2} s^T (\sigma^2 \Sigma_{ee}^{-1} + N^{-1}) s < 1 \quad || \quad (15)$$

### Future Studies

In the classical approach, estimation with linear models involves fixed (nonstochastic parameters). It is, however, equally likely that short-term deformations are random realizations of long-term deformations. If such a proposition can be ascertained to be relevant, then other approaches should be followed.

In the future, studies consonant with the above possibility, two predictors, proposed by Schaffrin [1983], (rather than estimators), namely, Homogeneous Best Linear Unbiased Predictor (HOMBLUP) and Homogeneous Best Linear Predictor (HOMBLIP) will be examined.

### References

- Teräsvirta, T. (1979), "Some Results of Improving the Least Squares Estimation of Linear Models by Mixed Estimation," discussion paper 7914, Louvain, CORE.
- Theil, H. and A.S. Goldberger (1961), "On Pure and Mixed Estimation in Economics," *Int. Economics Rev.* 2, 65-78.
- Schaffrin, B. (1983), "Model Choice and Adjustment Techniques in the Presence of Prior Information," Ohio State Univ. Dept. of Geodetic Science and Surveying Rep. 337, Columbus.



## 2.4 GPS Positioning Software

The GPS interferometric positioning software at The Ohio State University was designed to process Macrometer™ observations in the single-, double- and triple-differenced phase modes with the capability of estimating relative positions of stations and baseline length, along with their statistics. Inter-station clock epoch offsets are also estimated in the single-difference mode. The correlations between double observables and between triple observables are taken into account. Cycle slips are considered by introducing additional bias (ambiguity) unknowns in the adjustment.

Test computations were made, using the mainframe IBM 3081-D computer to determine ten baselines ranging in length from 2-20 km. The OSU baseline solutions agree well with those of the National Geodetic Survey. The results demonstrate that the double-difference mode with bias (ambiguity) fixed provides the best solution among all processing modes so far developed. The single-difference mode, the double-difference mode with bias (ambiguity) free and the triple difference mode are, in the case of no cycle slips, capable of determining the baselines with the same accuracy. In addition, the clock offset can be estimated to subnanoseconds.

The results of this research will be presented at the Conference on Positioning with GPS-1985, Rockville, Maryland, April 15-19, 1985, and will be published in the proceedings.

### 3. PERSONNEL

**Ivan I. Mueller, Project Supervisor, part time**

**Brent Archinal, Graduate Research Associate, part time**

**George Dedes, Graduate Research Associate, part time**

**Huseyin Baki Iz, Graduate Teaching Associate, without compensation**

**Burkhard Schaffrin, Visiting Researcher, without compensation, February 25 -  
March 8, 1985**

**Irene B. Tesfai, Secretary, part time**

**Ziqing Wei, Visiting Researcher, without compensation**

#### 4. TRAVEL

**Ivan I. Mueller**

**College Park, Maryland**

**October 29-31, 1985**

To attend Geopotential Research Mission (GRM) Science Conference.

**No Project support.**

**Ivan I. Mueller**

Maracaibo, Venezuela

**February 11 - 14, 1985**

To attend the International Symposium on Recent Crustal Movements  
and to represent the IAG.

No project support.

**Ivan I. Mueller**

**Greenbelt, Maryland**

Mar 19-20, 1985

To attend the Crustal Dynamics Working Group Meeting at Goddard Space Flight Center.

## 5. REPORTS PUBLISHED TO DATE

OSU Department of Geodetic Science Reports published

- 262 The Observability of the Celestial Pole and Its Nutations  
by Alfred Leick  
June, 1978
- 263 Earth Orientation from Lunar Laser Range-Differencing  
by Alfred Leick  
June, 1978
- 284 Estimability and Simple Dynamical Analyses of Range (Range-Rate and Range-Difference) Observations to Artificial Satellites  
by Boudewijn H.W. van Gelder  
December, 1978
- 289 Investigations on the Hierarchy of Reference Frames in Geodesy and Geodynamics  
by Erik W. Grafarend, Ivan I. Mueller, Haim B. Papo, Burghard Richter  
August, 1979
- 290 Error Analysis for a Spaceborne Laser Ranging System  
by Erricos C. Pavlis  
September, 1979
- 298 A VLBI Variance-Covariance Analysis Interactive Computer Program  
by Yehuda Bock  
May, 1980
- 299 Geodetic Positioning Using a Global Positioning System of Satellites  
by Patrick J. Fell  
June, 1980
- 302 Reference Coordinate Systems for Earth Dynamics: A Preview  
by Ivan I. Mueller  
August, 1980
- 320 Prediction of Earth Rotation and Polar Motion  
by Sheng-Yuan Zhu  
September, 1981
- 329 Reference Frame Requirements and the MERIT Campaign  
by Ivan I. Mueller, Sheng-Yuan Zhu and Yehuda Bock  
June, 1982
- 337 The Use of Baseline Measurements and Geophysical Models for the Estimation of Crustal Deformations and the Terrestrial Reference System  
by Yehuda Bock  
December, 1982

- 338 On the Geodetic Applications of Simultaneous Range-Differencing to Lageos  
by Erricos C. Pavlis  
December, 1982
- 340 A Comparison of Geodetic Doppler Satellite Receivers  
by Brent A. Archinal  
November, 1982  
(partial support)
- 348 On the Time Delay Weight Matrix in VLBI Geodetic Parameter Estimation  
by Yehuda Bock  
July, 1983
- 351 Model Choice and Adjustment Techniques in the Presence of Prior  
Information  
by Burkhard Schaffrin  
September, 1983

The following papers were presented at various professional meetings and/or published:

"Concept for Reference Frames in Geodesy and Geodynamics"

AGU Spring Meeting, Miami Beach, Florida, April 17-21, 1978

IAU Symposium No. 82, Cadiz, Spain, May 8-12, 1978

7th Symposium on Mathematical Geodesy, Assisi, Italy, June 8-10, 1978

"Concepts for Reference Frames in Geodesy and Geodynamics: The Reference Directions," Bulletin Geodesique, 53 (1979), No. 3, pp. 195-213.

"What Have We Learned from Satellite Geodesy?"

2nd International Symposium on Use of Artificial Satellites for Geodesy and Geodynamics, Lagonissi, Greece, May 30 - June 3, 1978

"Parameter Estimation from VLBI and Laser Ranging"

IAG Special Study Group 4.45 Meeting on Structure of the Gravity Field Lagonissi, Greece, June 5-6, 1978

"Estimable Parameters from Spaceborne Laser Ranging"

SGRS Workshop, Austin, Texas, July 18-23, 1978

"Defining the Celestial Pole," manuscripta geodaetica, 4 (1979), No. 2 pp. 149-183.

"Three-Dimensional Geodetic Techniques"

Technology Exchange Week, Inter-American Geodetic Survey

Fort Clayton, Canal Zone, May 14-19, 1979

published in Spanish as "Técnicas Geodesicas Tridimensionales," Memoria de la Semana de Intercambio Tecnológico, Panama, Rep. de Panama, pp. 400-426.

"On the VLBI-Satellite Laser Ranging 'Iron Triangle' Intercomparison Experiment," Meeting on Radio Interferometry Techniques for Geodesy, Massachusetts Institute of Technology, Cambridge, June 19-21, 1979

"Space Geodesy for Geodynamics, A Research Plan for the Next Decade"

Sonderforschungsbereich - Satellitengeodäsie - SFB 78

Colloquium in Viechtach, FRG, October 23-24, 1979

"Concept of Reference Frames for Geodesy and Geophysics"

seminar given at University of Stuttgart, West Germany, June 19, 1980

"Space Geodesy and Geodynamics,"

seminar given at University of Stuttgart, West Germany, June 26, 1980

"Geodetic Applications of the Global Positioning System of Satellites and Radio Interferometry," seminar given at University of Stuttgart, West Germany, July 3, 1980

"Reference Coordinate Systems for Earth Dynamics: A Preview,"

Proc. of IAU Colloquium 56 on Reference Coordinate Systems for Earth Dynamics," September 8-12, 1980, Warsaw, Poland, E.M. Gaposchkin and B. Kożaczek, eds., D. Reidel. Presented at AGU, San Francisco, December, 1980.

"Comments on Conventional Terrestrial and Quasi-inertial Reference Systems," with J. Kovalevsky, Proc. of IAU Colloquium 56 on Reference Coordinate Systems for Earth Dynamics, September 8-12, 1980, Warsaw, Poland, E.M. Gaposchkin and B. Kożaczek, eds., D. Reidel.

"Precise Positioning with GPS"

seminar given at Deutsche Geodätische Forschungsinstitut, Munich, West Germany, September 18, 1980

"Técnicas Geodesicas Tridimensionales"

(translated from English by IAGS), ASIA Journal (Asociacion Salvadorena de Ingenieros y Arquitectos) San Salvador, No. 61, Oct. 80, pp. 40-51; cont'd in No. 62, Dec. 80, pp. 31-39.

"Space Geodetic Techniques and Geodynamics"

Proc. 1st International Symposium on Crustal Movements in Africa Addis Ababa, Ethiopia, May 5-16, 1981

"Comparison of Polar Motion Data from the 1980 Project MERIT Short Campaign"

Proc. of IAU Colloquium 63 on "High Precision Earth Rotation and Earth-Moon Dynamics: Lunar Distances and Related Observations," May 22-27, 1981, Grasse, France, D. Reidel (I.I. Mueller, B.S. Rajal and S.Y. Zhu)

"Geodesy and the Global Positioning System"

Proc. of IAG Symposium on Geodetic Networks and Computations, Aug. 31-Sept. 5, 1981, Munich (I.I. Mueller and B. Archinal), ed. R. Sigl, Vol. IV, pp. 28-36, Deutsches Geodätische Komm., Reihe B, 258/IV, 1982.

"The Future of Space Techniques in Geodesy and Geodynamics," 2nd Symp. on Geodesy in Africa, Nairobi, November 9-20, 1982 (Ivan I. Mueller).

"Use of Simultaneous Doppler-Derived Ranges in the Geometric Mode," Proc. of 3rd International Geodetic Symp. on Satellite Doppler Positioning, Las Cruces, New Mexico, Feb. 8-12, 1982 (R. Schneeberger, D. Pavlis and I.I. Mueller)

"A Comparison of Geodetic Doppler Satellite Receivers"

Proc. of 3rd International Geodetic Symp. on Satellite Doppler Positioning, Las Cruces, New Mexico, Feb. 8-12, 1982 (Brent Archinal and Ivan I. Mueller)

"Glacial Movement Measurements in Greenland by Satellite Doppler Geodetic Receivers," Third Symp. on the Study of Movements in Engineering Surveys, August 25-27, 1982, Budapest, Hungary (Alice Drew, Ivan I. Mueller and Ian Whillans)

"On the Establishment and Maintenance of a Modern Conventional Terrestrial Reference System," Proc. of Symp. No. 5: Geodetic Applications of Radio Interferometry, IAG, Tokyo, May 7-8, 1982, NOAA Technical Rep. NOS 95 NGS 24, pp. 36-45 (Y. Bock and S.Y. Zhu)

"Comments on 'Frequency Modulation of the Chandlerian Component of Polar Motion' by William E. Carter," JGR, 87(B13), Dec. 10, 1982 (S.Y. Zhu)

"Effects of Adopting New Precession, Nutation and Equinox Corrections on the Terrestrial Reference Frame," XVIII General Assembly of the IAU, Patras, Greece, August, 1982. Bulletin Geodesique, 57, 1, (1983) (Sheng-Yuan Zhu and Ivan I. Mueller)

"Lectures on the Terrestrial Reference Frame," Third International Summer School in the Mountains on Geodesy and Global Geodynamics, Admont, Austria, Aug. 30 - Sept. 10, 1982, Geodesy and Global Geodynamics, H. Moritz and H. Sünkel, eds., TU Graz, 41, pp. 67-166

"Geometric Adjustment of Simultaneous Doppler-Derived Range Differences," Third International Symp. on the Use of Artificial Satellites for Geodesy and Geodynamics, Porto Hydra, Greece, Sept. 20-25 (C. Zhang and I.I. Mueller)

"Results of a Comparison of Geodetic Doppler Satellite Receivers," Third International Symp. on the Use of Artificial Satellites for Geodesy and Geodynamics, Porto Hydra, Greece, Sept. 20-25 (Brent A. Archinal and Ivan I. Mueller)

"The Effect of Earth Orientation Errors in Baseline Determination," Annual Fall Meeting of the American Geophysical Union, San Francisco, Dec. 7-15, 1982, and Fifth Annual NASA Geodynamics Program Conference and Crustal Dynamics Project Review, Washington, D.C., Jan. 24-28, 1983, Bulletin Geodesique, 57, 3 (1983) (Erricos C. Pavlis and Ivan I. Mueller)

"Estimating Crustal Deformations from a Combination of Baseline Measurements and Geophysical Models," Bulletin Geodesique, 57, 3, 1983 (Yehuda Bock)

"Report of the IAG/IAU Joint Working Group on the Establishment and Maintenance of a Conventional Terrestrial Reference System (COTES)," Proc. of IAG Symposia, XVIII General Assembly, Hamburg, 1983, Vol. 2

"On the Geodetic Applications of Simultaneous Range-Differencing to Lageos" Annual Fall Meeting of the AGU, San Francisco, December, 1983. Journal of Geophysical Research, in press (Erricos C. Pavlis).

"Baseline Determination from Simultaneous Lageos Ranging," Annual Spring Meeting of the AGU, Cincinnati, May, 1984 (Erricos C. Pavlis)

"International Coordination of Space Techniques for Geodesy and Geodynamics," Keynote Speech, International Symposium on Space Techniques for Geodynamics, Sopron, Hungary, July 9-13, 1984

"Reference Systems, Collocations and Ties," 5th International Workshop on Laser Ranging Instrumentation, Royal Greenwich Observatory, September 8-14, 1984

"Space Geodesy and Geodynamics, Present and Future," Helmert Commemorative Lecture, 5th International Symposium on Geodesy and Physics of the Earth, Magdeburg, GDR, September 23-29, 1984